# Mixed harmonic charge dependent azimuthal correlations in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV measured with the ALICE experiment at the LHC

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**Abstract**

Mixed harmonic charge dependent azimuthal correlations at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV were measured with the ALICE detector at the LHC. A clear charge dependence for a series of correlations is observed both via the multi-particle cumulant and the event plane methods. Implications from these measurements for the possible effects of the local parity violation in QCD and for models which incorporate the azimuthal anisotropic flow and the local charge conservation on the kinetic freeze-out surface are discussed.

## 1. Introduction

The charge dependence of the azimuthal correlations between produced hadrons is an important probe of the QGP matter created in relativistic heavy-ion collisions. It is in particular sensitive to the interplay between the local charge conservation (LCC) induced correlations and azimuthally asymmetric radial expansion of the collision system [1]. This further helps to discriminate effects from charges produced earlier in the collision by the gluon string fragmentation and late in the collision by the hadronization of the expanding QGP matter.

Recently, it was argued that the charge dependent azimuthal correlations can be also sensitive to the possible effect of the local parity violation in QCD [2]. Parity violation in QCD may happen as a result of the interaction between produced quarks and topologically non-trivial gluonic field configurations. In the presence of the strong magnetic field generated in a heavy-ion collision, the local parity violation may result in a separation of charges along the magnetic field which points perpendicular to the reaction plane. This phenomenon is called the Chiral Magnetic Effect (CME).

An important observable as a sensitive probe of the CME is the two particle correlation with respect to the reaction plane $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP})\rangle$ [3], where the bracket denotes the average over all particles in all events and the indices $\alpha$ and $\beta$ refer to the charge of the particles. $\varphi_{\alpha,\beta}$ is the azimuthal angle of the charged particles and $\Psi_{RP}$ is the reaction plane angle. Measurements by the STAR Collaboration revealed non-zero correlation $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP})\rangle$, which is consistent with qualitative expectations from the CME [4]. At the same time, a study [1] showed that a

[1]A list of members of the ALICE Collaboration and acknowledgements can be found at the end of this issue.

significant part of the observed charge dependence can be described by the Blast Wave model incorporating effects of the LCC. On the other hand, the charge independent part of this correlation may have contributions from the dipole flow fluctuations and effects of momentum conservation [5, 6]. At the moment, none of the models can reproduce simultaneously the charge dependent and independent parts of the observed correlations. Recently the ALICE Collaboration released a paper [7] where the correlation $\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \rangle$ were measured at LHC energies. In these proceedings, we extent the ALICE measurement to the additional mixed harmonic charge dependent correlations with respect to the collision symmetry plane, which may help to disentangle the CME and LCC induced correlations [9].

## 2. Analysis details

A sample of about 13 M minimum bias Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV collected by the ALICE detector during the 2010 LHC run was analyzed. Description of the ALICE detector and details about collision triggers and centrality determination can be found in [7, 8]. A Time Projection Chamber (TPC) is used to reconstruct charged particles in the kinematic range $|\eta| < 0.8$ and $p_T > 0.2$ GeV/$c$. Correlations with respect to the symmetry plane were measured using the event plane and multi-particle cumulant methods. In the event plane method, the symmetry planes were estimated from azimuthal distributions of hits in two forward scintillator counters (VZERO) which cover the pseudo-rapidity range $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$, and two Forward Multiplicity Detectors (FMD) located at $1.7 < \eta < 5.1$ and $-3.4 < \eta < -1.7$. In the multi-particle cumulant method, the correlations with respect to the symmetry plane are evaluated from the azimuthal angle correlations of charged particles reconstructed by the TPC. Although the dominant systematic errors come from the event plane determinations, we observed good agreement between results from two different methods.

## 3. Results

The centrality dependence of the correlations $\langle \cos(\varphi_\alpha - \varphi_\beta) \rangle$ and $\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \rangle$ for the same and opposite charge combinations measured for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV was reported by ALICE in [6]. For the correlation $\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \rangle$, ALICE observed that the same charge correlation is non-zero and negative, while the opposite charge correlation has a significantly smaller magnitude and is positive for peripheral collisions. ALICE also showed that there is little collision energy dependence when comparing results to that at the top RHIC energy. Even though some of the features of the observed correlations are in qualitative agreement with the expectation from the CME, the origin of these correlations is still not clear since they are sensitive to many other parity-conserving physics mechanisms. To study the physics backgrounds for the CME search, ALICE has measured the two particle correlation $\langle \cos(\varphi_\alpha - \varphi_\beta) \rangle$, which also shows strong charge dependence but its correlation strength is significantly different from what was measured by the STAR Collaboration at lower collision energy. As shown in Fig.1 and 2, measurements were extended to a set of charge dependent correlations $\langle \cos[\varphi_\alpha - (m+1)\varphi_\beta + m\Psi_k] \rangle$ where $m, k$ are integers and $\Psi_k$ is the $k$-th order collision symmetry plane angle. They help to better constrain the possible physical contributions to the previously measured correlation $\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \rangle$. Note that the charge independent baseline correlation $\langle \cos(\varphi_\alpha - 3\varphi_\beta + 2\Psi_2) \rangle$ is related to the widely discussed effects of flow fluctuations and inter-correlation between the collision symmetry planes [5, 10].

The model in Fig.3 with parameters tuned on the measured hadron spectra and the anisotropic

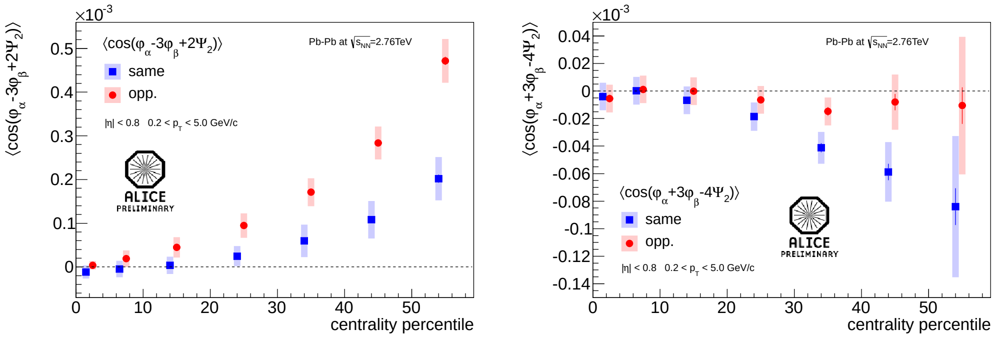


Figure 1: Centrality dependence of the charge dependent two particle azimuthal correlations with respect to the 2nd order symmetry plane $\Psi_2$: (left) $\langle\cos(\varphi_\alpha - 3\varphi_\beta + 2\Psi_2)\rangle$, (right) $\langle\cos(\varphi_\alpha + 3\varphi_\beta - 4\Psi_2)\rangle$.

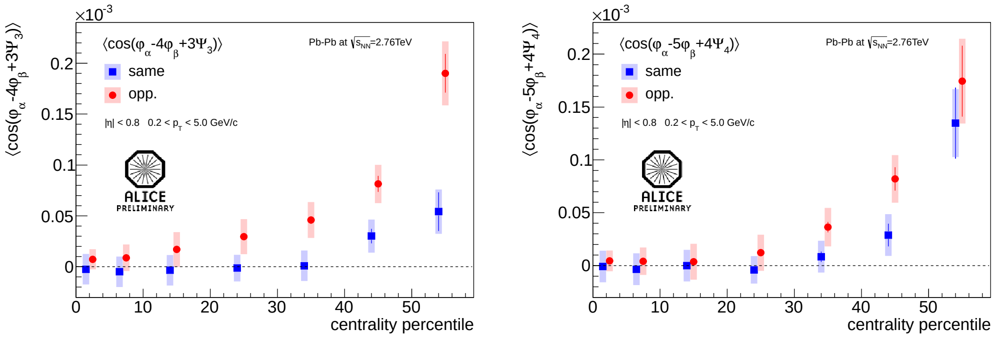


Figure 2: Centrality dependence of the charge dependent two particle azimuthal correlations with respect to the 3rd and 4th order symmetry plane $\Psi_{3,4}$: (left) $\langle\cos(\varphi_\alpha - 4\varphi_\beta + 3\Psi_3)\rangle$, (right) $\langle\cos(\varphi_\alpha - 5\varphi_\beta + 4\Psi_4)\rangle$.

flow at the LHC reproduces the features of the charge dependence of the correlations $\langle\cos(\varphi_\alpha - \varphi_\beta)\rangle$ and $\langle\cos[\varphi_\alpha - (m+1)\varphi_\beta + m\Psi_2]\rangle$, but fails to describe the higher moments $\langle\cos[n(\varphi_\alpha - \varphi_\beta)]\rangle$ for $n > 1$ [9]. This indicates that a significant part of the correlations observed for $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP})\rangle$ may originate from the LCC induced correlation. However, more studies are needed to quantify its actual contribution. ALICE also measured a charge dependence of the double-harmonic correlation $\langle\cos(2\varphi_\alpha + 2\varphi_\beta - 4\Psi_4)\rangle$ which also may help in disentangling effects from the LCC and the CME [11].
Similarly to the differential correlations for $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP})\rangle$ reported in [7], ALICE observes that the other correlations $\langle\cos(\varphi_\alpha - 3\varphi_\beta + 2\Psi_{RP})\rangle$ are localized within about one unit of rapidity (or may even change sign as a function of $\Delta\eta$) and extend up to the higher $p_T$ of the pair as shown in Fig.4.

## 4. Summary

Charge dependent azimuthal correlations in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV were measured by the ALICE Collaboration. A significant non-zero correlation $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP})\rangle$ was observed, which was originally proposed as an observable sensitive to the CME and thus to effects from the local parity violation in QCD. The experimental analysis was extended to the

higher moments of the two particle azimuthal correlations $\langle\cos[n(\varphi_\alpha - \varphi_\beta)]\rangle$ for $n$ =1-4 and to the mixed harmonic charge dependent azimuthal correlations with respect to the 2nd, 3rd, and 4th order collision symmetry planes (e.g. $\langle\cos(\varphi_\alpha - 3\varphi_\beta + 2\Psi_2)\rangle$). These new results provide an important experimental input which is relevant to the study of various physics mechanism responsible for the charge dependence of the azimuthal correlations among particles produced in a heavy-ion collision, such as the CME, local charge conservation, and flow fluctuations.

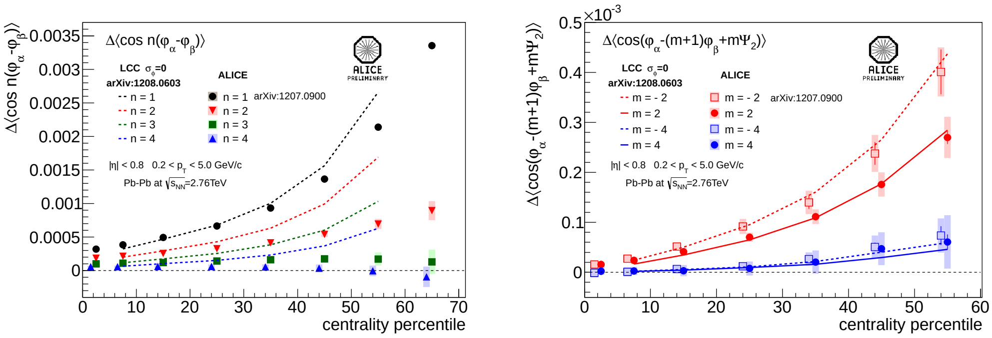


Figure 3: Centrality dependence of the correlation $\Delta\langle\cos[n(\varphi_\alpha - \varphi_\beta)]\rangle$ (left) and $\Delta\langle\cos[\varphi_\alpha - (m+1)\varphi_\beta + m\Psi_2]\rangle$ (right) in comparison with the Blast Wave model incorporating effects of the LCC [9]. Here $\Delta$ denotes the difference between the same and opposite charge correlations.

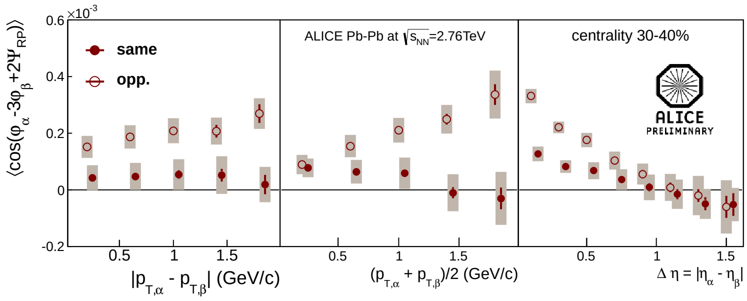


Figure 4: The pair differential correlation $\langle\cos(\varphi_\alpha - 3\varphi_\beta + 2\Psi_{RP})\rangle$ as a function of (left) the transverse momentum difference $|p_{T,\alpha} - p_{T,\beta}|$, (center) the average transverse momentum $(p_{T,\alpha} + p_{T,\beta})/2$, (right) the rapidity separation $\Delta\eta = |\eta_\alpha - \eta_\beta|$ of the charged particle pair.

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